Starburst-AGN Connection: A Lesson from High-z Powerful Radio Galaxies

Yoshiaki Taniguchi
Astronomical Institute, Graduate School of Science, Tohoku University, Aramaki, Aoba, Sendai 980-8578, Japan

ABSTRACT

Powerful radio galaxies at high redshift are highly useful in studies of early evolution of AGN-hosting galaxies because their observed optical and near infrared light are dominated by their stellar population rather than the nonthermal continuum emitted by the central engine of AGNs. In addition, the presence of AGN activity in them implies that a supermassive black hole has been already made in their nuclei. These properties allow us to investigate a possible starburst-AGN connection in early universe and then provide some crucial hints for the formation mechanism of supermassive black holes. Taking observational properties of high-z powerful radio galaxies into account, we discuss a possible formation mechanism of supermassive black holes in their nuclei.

1. Introduction

The formation and evolution of supermassive black holes were once thought to be related only to some exotic phenomena such as nonthermal nuclear activity. Active galactic nuclei (AGNs), in particular, quasars and powerful radio galaxies, are basically minor populations among galactic nuclei. Therefore, it has long been presumed that the history of supermassive black holes (SMBHs) is independent from that of galaxies or that of stars. However, since the discovery of a massive dark object in the heart of Andromeda galaxy (M31; Dressler & Richstone 1988; Kormendy 1988), it has been reported that a number of nearby normal galaxies appear to have such a massive dark object in their nuclei (e.g., Kormendy & Richstone 1995).

Then, in the 90s, beautiful evidence for a SMBH was found in one of famous nearby AGNs, NGC 4258, based on kinematic motion of H_2O masing clouds around the nucleus (Miyoshi et al. 1995). Further challenge made in this decade has brought the discovery of a tight correlation between the spheroidal mass and the SMBH mass (Magorrian et al. 1998; see also Silk & Rees 1998). Surprisingly, normal galaxies and AGN-hosting galaxies follow the same correlation (Gebhardt et al. 2000; Ferrarese et al. 2001; Wandel 2002). This suggests that most *nucleated* galaxies have a massive dark object, a SMBH, despite of the nonthermal nuclear activity. It is also suggested that AGN phenomena are not associated with the formation process of a SMBH itself (e.g., Taniguchi 2002). More importantly, the formation of SMBHs may be physically linked to that of spheroidal component of galaxies. In order to explore this issue, it seems important to investigate young galaxies in early universe. For this purpose, we use observational properties of high-z powerful radio galaxies[1] (HzPRGs) because their host galaxies have been intensively investigated for these two decades (e.g., McCarthy 1993) and consider a possible scenario for the the formation of SMBHs at high redshift (see for review, Rees 1984; Haiman & Quataert 2004).

[1]The most distant HzPRG known to date is TN J0924−2201 (van Breugel et al. 1999). However, most HzPRGs are located at $z \sim 2$ - 4 (e.g., McCarthy 1993).

2. Nature of High-z Powerful Radio Galaxies

HzPRGs have been often used to investigate stellar populations in young galaxies because their optical and NIR continuum emission is dominated by host stars rather than the nonthermal continuum emitted from the central engine of AGNs (see, for a review, McCarthy 1993; see also Iwamuro et al. 2003 and references therein). Another reason why HzPRGs are useful in investigations of starburst-AGN connection in early universe is that their host galaxies appear to experience of passive evolution. Since their hosts are basically massive populations (i.e., their local analogue are giant elliptical galaxies), they can be used to investigate possible early connection between vigorous star formation activity and early formation of a SMBH.

We summarize several lines of evidence for the passive evolution of HzPRG host galaxies. First evidence comes from evolution of optical/NIR spectral energy distributions (SEDs) of radio galaxies from high redshift to the present day. In Figure 1, we show the SED evolution of radio galaxies analyzed by Yoshii et al. (1994). It is shown that host galaxies at high redshift tend to have blue SEDs (i.e., dominated by massive young stars) while those in nearby universe tend to have red ones (i.e., dominated by cool, old stars). This trend suggests strongly that hosts of radio galaxies have experienced the passive evolution. The second evidence is that the submm (850μm) luminosity of radio galaxies shows a monotonic decrease with decreasing redshift from $z \sim 4$ to $z \sim 0$ (Archibald et al. 2001). This property seems consistent with a scenario that the first major epoch of star formation in massive hosts of radio galaxies occurred at similar redshift and then evolved passively without another episodic massive starburst during the course of their evolution. The third evidence is that a number of HzPRGs are very luminous in FIR and/or submm (e.g., $L_{\rm FIR} > 10^{12} L_{\odot}$, suggesting that very luminous starbursts occurred in the gas-rich hosts (Archibald et al. 2001; De Breuck et al. 2003 and references therein). This also suggests that HzPRGs are basically similar to ultraluminous infrared galaxies in the local universe that experience *dissipative collapse* in their hosts (Kormendy & Sanders 1992). The fourth evidence comes from the probable superwind activity in HzPRGs (e.g., Motohara et al. 2000; Taniguchi et al. 2001; see also De Breuck et al. 2000) because such large-scale superwinds could be attributed to a very luminous starburst in their hosts (Larson 1974; Arimoto & Yoshii 1987). Since all these results are obtained by using fairly large samples of radio galaxies, one may conclude that hosts of *most* radio galaxies were very massive even at such high redshift and then experienced the passive evolution after their initial starburst.

The above argument seems to be inconsistent with hierarchical clustering scenarios that have been accepted as a reliable mass assembly history (e.g., Kauffmann et al. 1999). However, recent submm surveys carried out with SCUBA on JCMT have found a number of massive galaxies either with ultra (or hyper) luminous starbursts or AGN at high redshift. Any current hierarchical models underpredict the number of such massive galaxies in early universe (e.g., Genzel et al. 2004). Therefore, it turns out that some massive galaxies were already assembled at high redshift and then evolved passively to the present day. If this is the case, it is expected that hosts of HzPRGs were born at very high redshift (e.g., $z \sim 10$) and most stars were formed within a short duration in their early phase. After this initial starburst, through the superwind phase, they passively evolved to the present-day massive giant elliptical galaxies in which the Magorrian relation is well established. If the formation of SMBHs in these galaxies wes tightly linked to the initial starburst event, it seems worth studying which physical mechanism played an important role in their initial starburst phase.

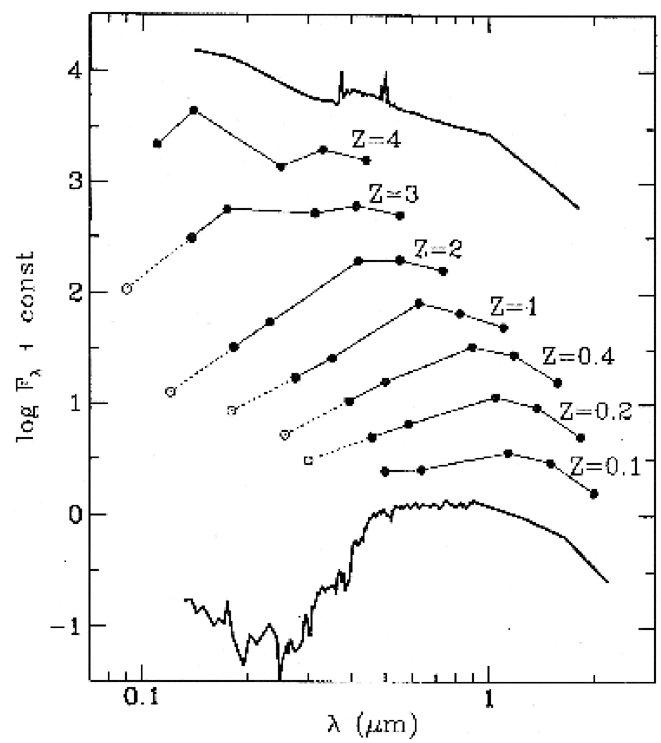

Fig. 1.— The evolution of optical/NIR spectral energy distributions of HzPRGs (Yoshii et al. 1994). The ordinate is in arbitrary units. The upper SED shows that of nearby Irregular galaxies while the lower SED shows that of nearby ellipticals.

3. Possible Scenario for the Early Formation of SMBHs

As discussed in the previous section, the observational properties of HzPRGs suggest that they could evolve to giant elliptical galaxies in the local universe. Since giant ellipticals follow the Magorrian relation, the following questions arise as; (i) *When was the Magorrian relation established ?*, and (ii) *How was the Magorrian relation established ?*. In order to give some answers to the above questions, we consider probable star formation history in the hosts of HzPRGs.

First, let us discuss the epoch of major star formation the HzPRG hosts. An important observational result is that many HzPRGs show Nitrogen overabundance in their ionized gaseous nebulae (Vernet et al. 2001). This property is also found in the broad line gas in high-z quasars (Hamann & Ferland 1993). As for high-z quasars, it is also known that Fe is more abundant with respect to α elements like Mg (Kawara et al. 1996; Dietrich et al. 2003). The N overabundance could be attributed to mass loss phenomena from intermediate mass stars. The Fe overabundance could be attributed to much contribution of Type Ia supernovae rather than Type II ones. Therefore these observations suggest that the epoch of major star formation could occur $\sim$ 1 Gyr before the observed epoch. Since typical redshifts of HzPRGs and high-z quasars are $z \sim 2$ - 4, the initial starburst could occur at $z \sim 5$ - 10 (Hamann & Ferland 1993; Yoshii et al. 1998).

Compact remnants, such as neutron stars and stellar-sized black holes, could be left after the death of massive stars formed in the initial starbursts. Mergers among such compact remnants could help in the mass growth of black holes (e.g., Taniguchi et al. 1999 and references therein). However, prior going to details of such mergers, it seems better to consider a possibility that much earlier formation of seed black holes because pre-galactic, Population III (Pop III) objects could form at very higher redshift, $z \sim 20$ - 30[2].

Recent theoretical investigations of Pop III objects have suggested that very massive stars could be born at the Pop III era, $M \sim 10^3 M_\odot$ (e.g., Bromm, Coppi, & Larson 2002; Abel, Bryan, & Norman 2002; Nakamura & Umemura 2003). If the stellar mass exceeds 260 $M_\odot$, such a very massive star could leave a compact remnant with mass of $\sim 100 M_\odot$ (Heger et al. 2003); i.e., the formation of an intermediate-mass black hole (IMBH; Taniguchi et al. 2000). If this is the case, such an IMBH could work as a first seed black hole, leading to the formation of a SMBH (Madau et al. 2004). Such very massive stars could be born in a dark matter halo with mass of $\sim 10^6 M_\odot$ at most (e., Fuller & Couchman 2000; Yoshida et al. 2003). Since the star formation efficiency could be low, it is unlikely that the growth of an IMBH can be made through successive mergers among many very massive stars and/or compact remnants. This suggests that the growth could be made by gas accretion onto an IMBH although the angular momentum transfer problem may exist.

The gas accretion (Eddington) timescale is estimated as $T_{\rm Edd} \sim 4 \times 10^7 (\eta/0.1)(L_{\rm Edd}/L)$ yr, where η is the radiation efficiency in rest-mass units, given that the gas accretion occurs at Eddington-luminosity limit (e.g., Krolik 1999). Let us assume that an IMBH was formed at $z_{\rm IMBH} = 25$. As stated before, typical redshifts of HzPRGs and high-z quasars are $z \sim 2$ - 4, and thus it is suggested that the initial starburst could occur around $z \sim 5$ - 10 in their hosts. For simplicity, we adopt the epoch of initial starburst in a host of HzPRGs, $z_{\rm initial} = 8$ and that of AGN activity, $z_{\rm AGN} = 3$. Given a flat universe with $\Omega_{\rm matter} = 0.3$, $\Omega_\Lambda = 0.7$, and $h_{70} = 1$ where $h_{70} = H_0/(70$ km s^{-1} Mpc$^{-1})$ based on the Wilkinson Microwave Anisotropy Probe (WMAP) Observations (Spergel et al. 2003), the time interval between $z_{\rm IMBH}$ and $z_{\rm initial}$, $\Delta T \simeq 6 \times 10^8$ yr. This time interval corresponds to $\sim 15 T_{\rm Edd}$. Therefore, if the Eddington-limited gas accretion could occur,

---

[2]Pop III objects could be born earlier than the cosmic reionization epoch, $z_{\rm reion} \sim 17$ (Spergel et al. 2003)

an IMBH could grow up to the mass of $M_\bullet \sim 10^5 M_{\rm IMBH} \sim 10^7 M_\odot$ at $z = 8$. At this redshift, successive mergers among dark matter mini halos could give rise to the formation of massive gaseous systems with $M \sim 10^{11} M_\odot$. If a few or several such gaseous systems could merge into one, it is expected that a very luminous starburst could occur near the merger center; note that ultraluminous infrared galaxies are local analogs of such merger-driven starbursts (e.g., Kormendy & Sanders 1992; see also Taniguchi, Ikeuchi, & Shioya 1999). Such merger-driven luminous starbursts can be caused by strong dynamical action of a binary or multiple SMBH system (Taniguchi & Wada 1996; Taniguchi & Shioya 1998). A large number of super star clusters could be formed in the central region of the merging system and they are expected to sink into the merger center[3], leading to the formation of a SMBH with $M_\bullet \sim 10^9 M_\odot$ within 1 Gyr (Ebisuzaki et al. 2001). Given the same flat universe, the time interval between $z = 8$ and $z = 3$ corresponds to 1.4 Gyr. Therefore, SMBHs can be made in the host galaxies of HzPRGs at $z = 3$.

4. Concluding Remarks

We summarize a possible scenario for the formation of a SMBH in nuclei of HzPRGs (as well as quasars) at $z \sim 3$ (see also Table 1).

Step I. A very massive star (i.e., a Pop III object) could born in a dark matter mini halo at $z \sim 25$. Shortly after the formation, an IMBH with $M_\bullet \sim 100 M_\odot$ could be left as a compact remnant; i.e., the first-stage seed black hole.

Step II. The gas accretion at the Eddington limit could grow up an IMBH to $M_\bullet \sim 10^7 M_\odot$ at $z \sim 8$ during the course of successive mergers among dark matter halos; this can be regarded as a seed SMBH. This growth takes 0.6 Gyr from $z \sim 25$.

Step III. A few or several massive gaseous system with $M \sim 10^{11} M_\odot$ could merge into one. In their final phase, a large number of super star clusters could be born near the merger center because of strong dynamical action driven by binary of multiple seed SMBHs.

Step IV. Such super star clusters could sink into the merger center because of dynamical friction, leading to the formation of a SMBH with $M_\bullet \sim 10^9 M_\odot$at $z \sim 3$. This process takes ~ 1 Gyr, being shorter than the time interval between $z = 8$ and $z = 3$ given the currently accepted WMAP cosmology.

The above scenario should be related to the formation of a massive giant elliptical galaxy. The very luminous starburst (or the initial starburst) could contribute to the formation of the spheroidal component. Therefore, the Magorrian relation could be established in the Step IV in this scenario. It is noted that such merger-driven ultraluminous starbursts could explain the Magorrian value of $M_\bullet/M_{\rm spheroid} \sim 0.001$ (Bekki & Couch 2001).

Acknowledgments

The author would like to thank Satoru Ikeuchi, Hideaki Mouri, Yasuhiro Shioya, and Piero Madau for useful discussion on possible formation mechanisms of supermassive black holes at high redshift. He

[3]Runaway mergers in some super star clusters may lead to the formation of IMBHs (e.g., Mouri & Taniguchi 2002)

also would like to thank Kazuo Makishima and Shin Mineshige for their kind invitation to this fruitful conference.

REFERENCES

Abel, T., Bryan, G. L., & Norman, M. L. 2002, Science, 295, 93

Archibald, E. N., Dunlop, J. S., Hughes, D. H., Rawlings, S., Eales, S. A., & Ivison, R. J. 2001, MNRAS, 323, 417

Arimoto, N., & Yoshii, Y. 1987, A & A, 173, 23

Bekki, K., & Couch, W. J. 2001, ApJ, 557, L19

Bromm, V., Coppi, P. S., & Larson, R. B. 2002, ApJ, 564, 23

De Breuck, C., et al. 2003, A&A, 401, 911

De Breuck, C., Röttgering, H., Miley, G., van Breugel, W., & Best, P. 2000, A&A, 362, 519

Dietrich, Hamann, F., Appenzeller, I., & Vestergaard, M. 2003, ApJ, 596, 817

Dressler, A., & Richstone, D. 1988, ApJ, 324, 701

Ebisuzaki, T., et al. 2001, ApJ, 562, L19

Ferrarese, L., Pogge, R. W., Peterson, B. M., Merritt, D., Wandel, A., & Joseph, C. L. 2001, ApJ, 555, L79

Fuller, T. M., & Couchman, H. M. P. 2000, ApJ, 544, 6

Gebhardt, K., et al. 2000, ApJ, 543, L5; Erratum, ApJ, 555, L75

Genzel, R., et al. 2004, astro-pj/0403183

Haiman, Z., & Quataert, E. 2004, astro-ph/0403225

Hamann, F., & Ferland, G. 1993, ApJ, 418, 11

Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. 2003, ApJ, 591, 288

Iwamuro, F., et al. 2003, ApJ, 598, 178

Kauffmann, G., et al. 1999, MNRAS, 303, 188

Kawara, K., Murayama, T., Taniguchi, Y., & Arimoto, N. 1996, ApJ, 470, L85

Kormendy, J. 1988, ApJ, 325, 128

Kormendy, J., & Richstone, D. 1995, ARA&A, 33, 581

Table 1. A Summary of the Proposed Scenario for the formation of SMBHs

z	$T_{\rm Univ}$ (Gyr)	ΔT (Gyr)	Event	$M_\bullet$ ($M_\odot$)
25	0.35		Pop. III $\Rightarrow$ IMBH	$\sim 10^2$
		0.55	gas accretion	
8	0.90		onset of mergers among massive halos	$\sim 10^7$
		1.40	starburst $\Rightarrow$ super star clusters	
3	2.30		sinking into the merger center	$\sim 10^9$

Krolik, J. H. 1999, Active Galactic Nuclei (Princeton University press), p. 127

Larson, R. B. 1974, MNRAS, 169, 229

Madau, P., Rees, M. J., Volonteri, M., Haardt, F., & Oh, S. P. 2004, ApJ, 604, 484

Magorrian, J., et al. 1998, AJ, 115, 2285

McCarthy, P. J. 1993, ARA&A, 31, 639

Miyoshi, M., Moran, J., Herrnstein, J., Greenhill, L., Nakai, N., Diamond, P., & Inoue, M. 1995, Nature, 373, 127

Motohara, K., et al. 2000, PASJ, 52, 33

Mouri, H., & Taniguchi, Y. 2002, ApJ, 566, L17

Nakamura, F., & Umemura, M. 2002, ApJ, 569, 549

Rees, M. J. 1984, ARA&A, 22, 471

Spergel, D. N., et al. 2003, ApJS, 148, 175

Silk, J., & Rees, M. J. 1998, A&A, 331, L1

Taniguchi, Y. 2002, in the Proceedings of the IAU 8th Asian-Pacific Regional Meeting, Vol. 1, ASP Conf. Ser., 289, 353

Taniguchi, Y., Ikeuchi, S., & Shioya, Y. 1999, ApJ, 514, L9

Taniguchi, Y., et al. 2001, ApJ, 559, L9

Taniguchi, Y., & Shioya, Y. 1998, ApJ, 501, L167

Taniguchi, Y., Shioya, Y., Tsuru, G. T., & Ikeuchi, S. 2000, PASJ, 52, 533

Taniguchi, Y., & Wada, K. 1996, ApJ, 469, 581

van Breugel, W., De Breuck, C., Stanford, S. A., Stern, D., Röttgering, H., & Miley, G. 1999, ApJ, 518, L61

Vernet, J., et al. 2001, A&A, 366, 7; Erratum, A&A, 370, 407

Wandel, A. 2002, ApJ, 565, 762

Yoshida, N., Abel, T., Hernquist, L., & Sugiyama, N. 2003, ApJ, 592, 645

Yoshii, Y., Renzini, A., Arimoto, N., & Taniguchi, Y. 1994, private communication

Yoshii, Y., Tsujimoto, T., & Kawara, K. 1998, ApJ, 507, L113